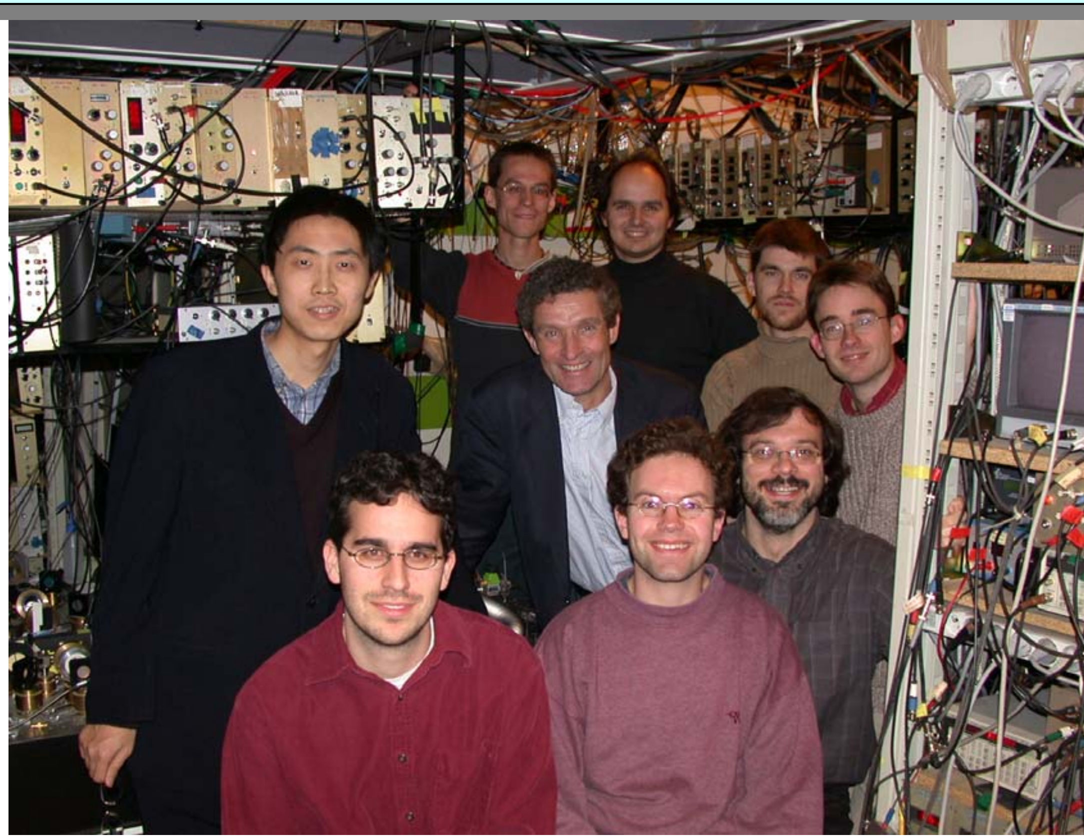
A study of the BEC-BCS crossover region with Lithium 6



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1530

Collège de France

T.Bourdel, L. Khaykovich, J. Cubizolles, J. Zhang, F. Chevy, M. Teichmann, L. Tarruell, S. Kokkelmans, Christophe Salomon

Theory: D. Petrov, G. Shlyapnikov, R. Combescot, Y. Castin

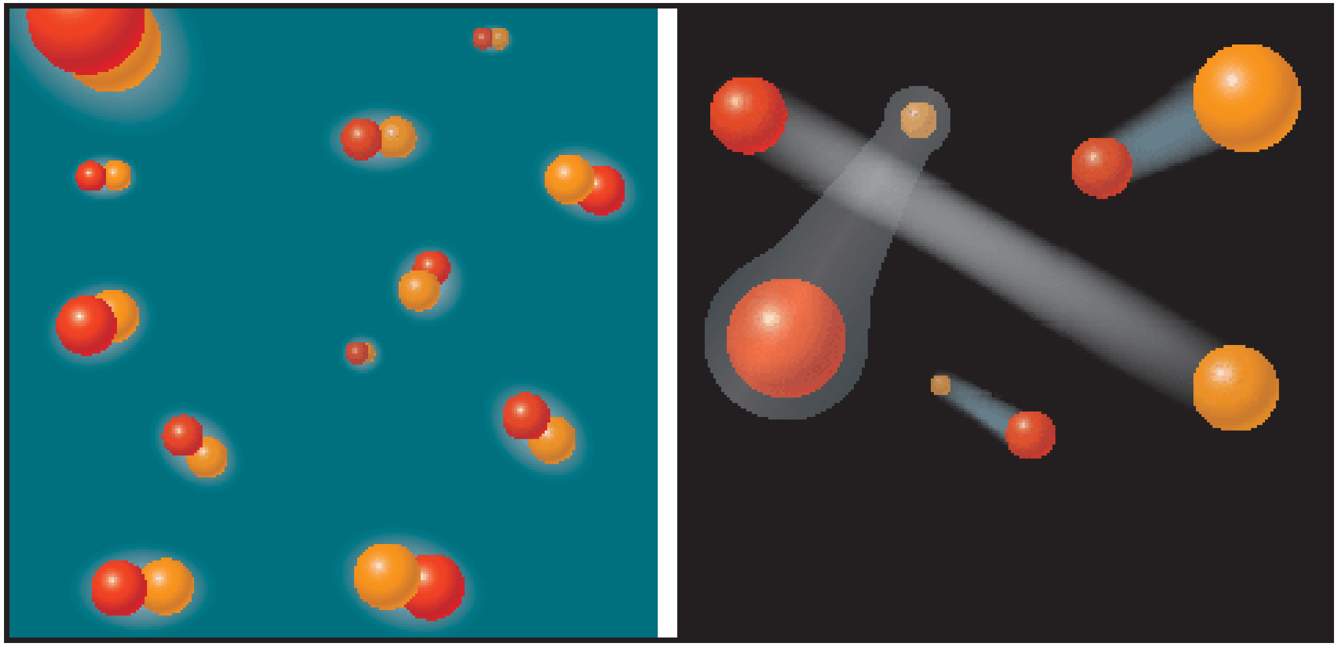
Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris,

Levico, March 4, 2004

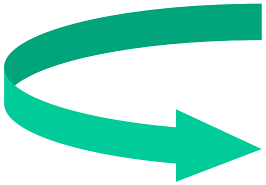
Molecular Bose-Einstein Condensate and Fermi Superfluidity

Two component Fermi gas at very low temperature
s-wave interaction, scattering length *a*

$a > 0$ | $a < 0$



Molecular BEC ? | Fermi superfluid ?



Feshbach resonance

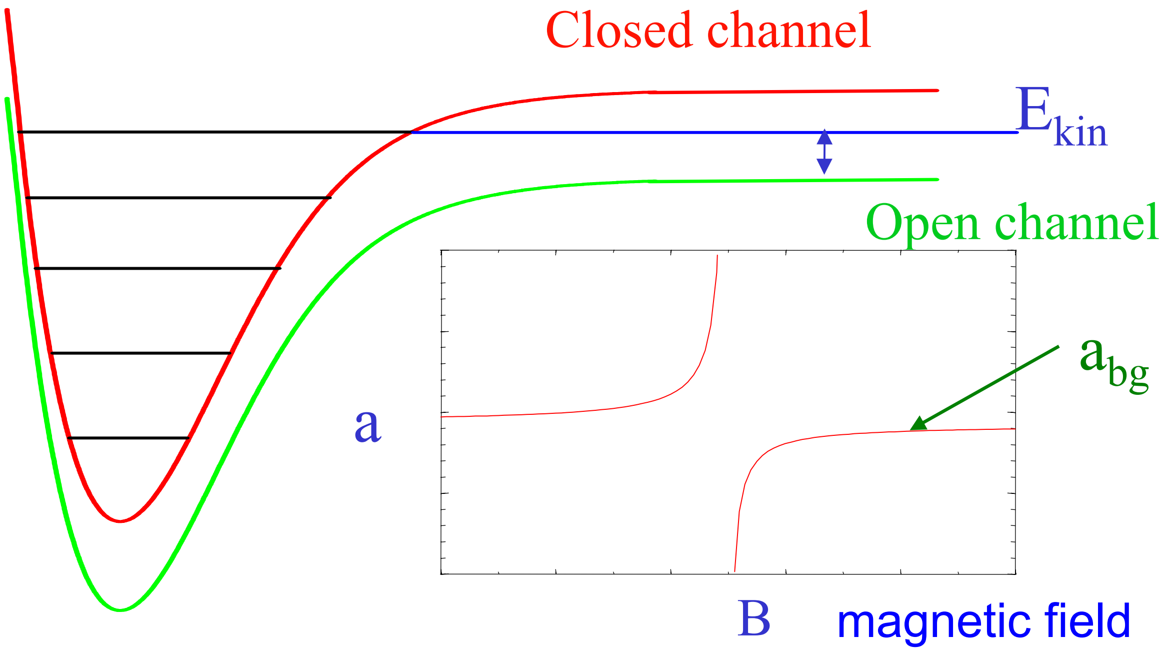
See Science news focus, August 8th, 2003

Outline

- Formation and detection of molecules
- Cooling to condensation
- Comparison with other molecular condensates
- Crossover between BEC of molecules and Fermi gas

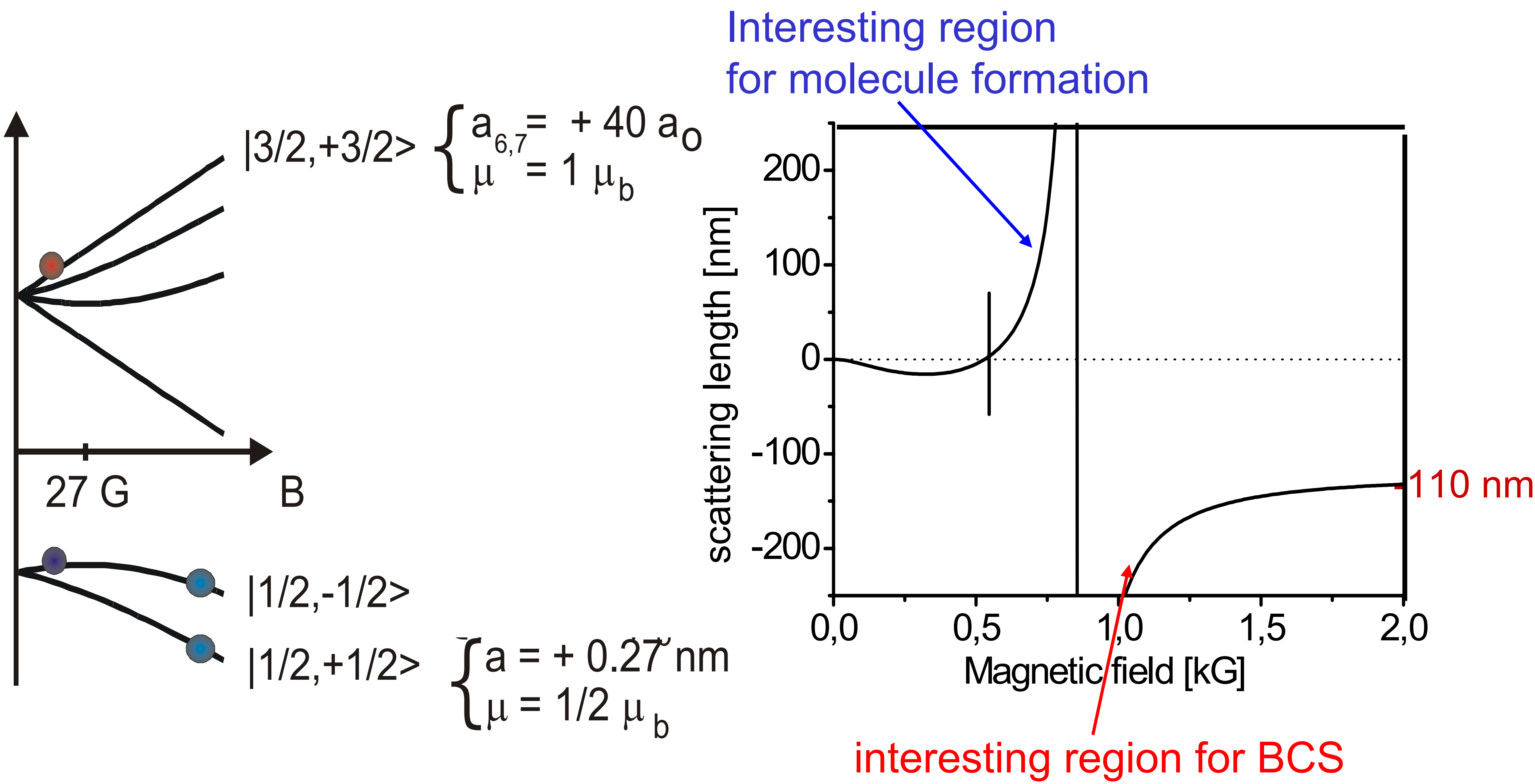
Feshbach Resonance

- Coupling between open channel and closed channel



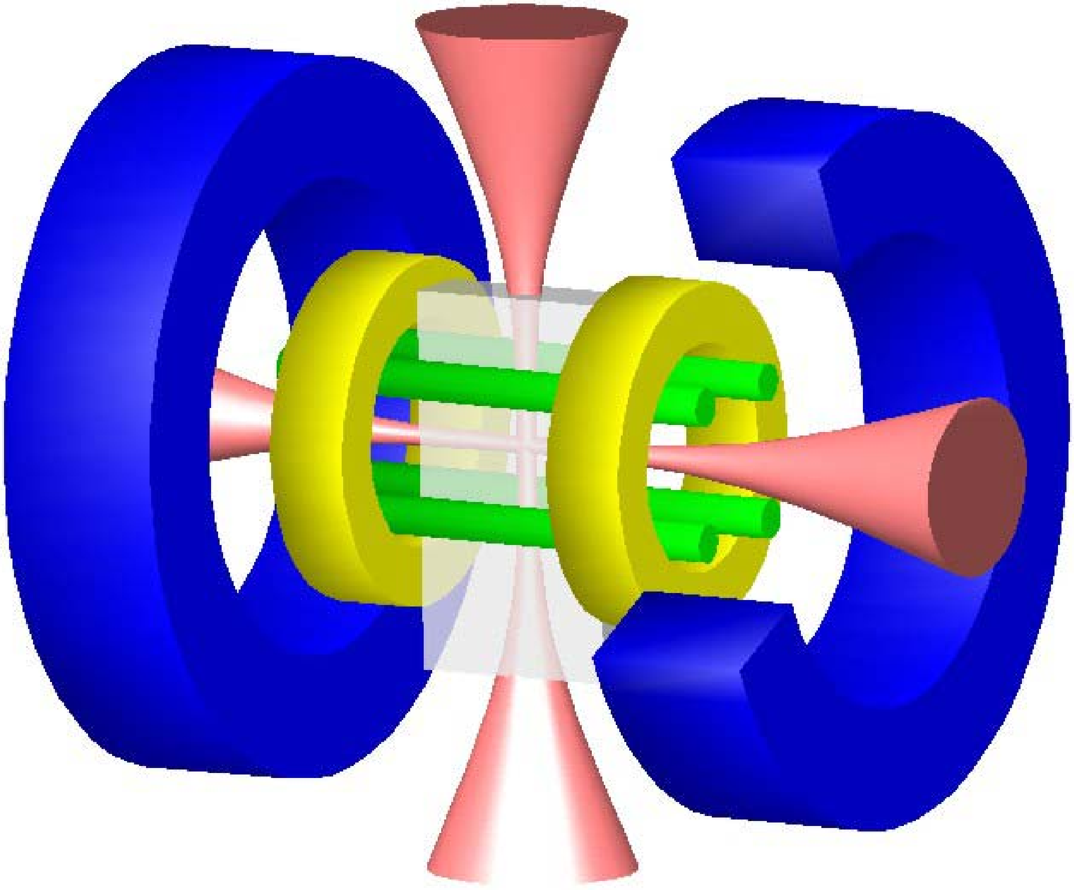
- Resonance: short range molecular state
- What is the lifetime of vibrational levels close to dissociation limit ?
- Scattering is strongly energy dependent

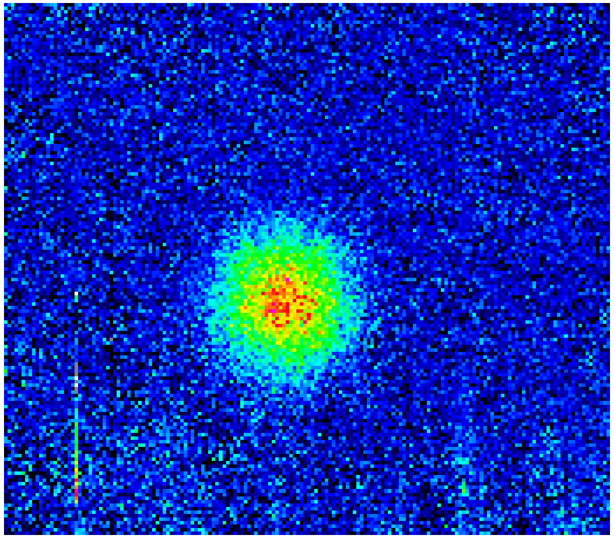
Lithium 6 Feshbach resonance



^{6}Lithium

Strongly interacting ^{6}Li gas in an optical trap



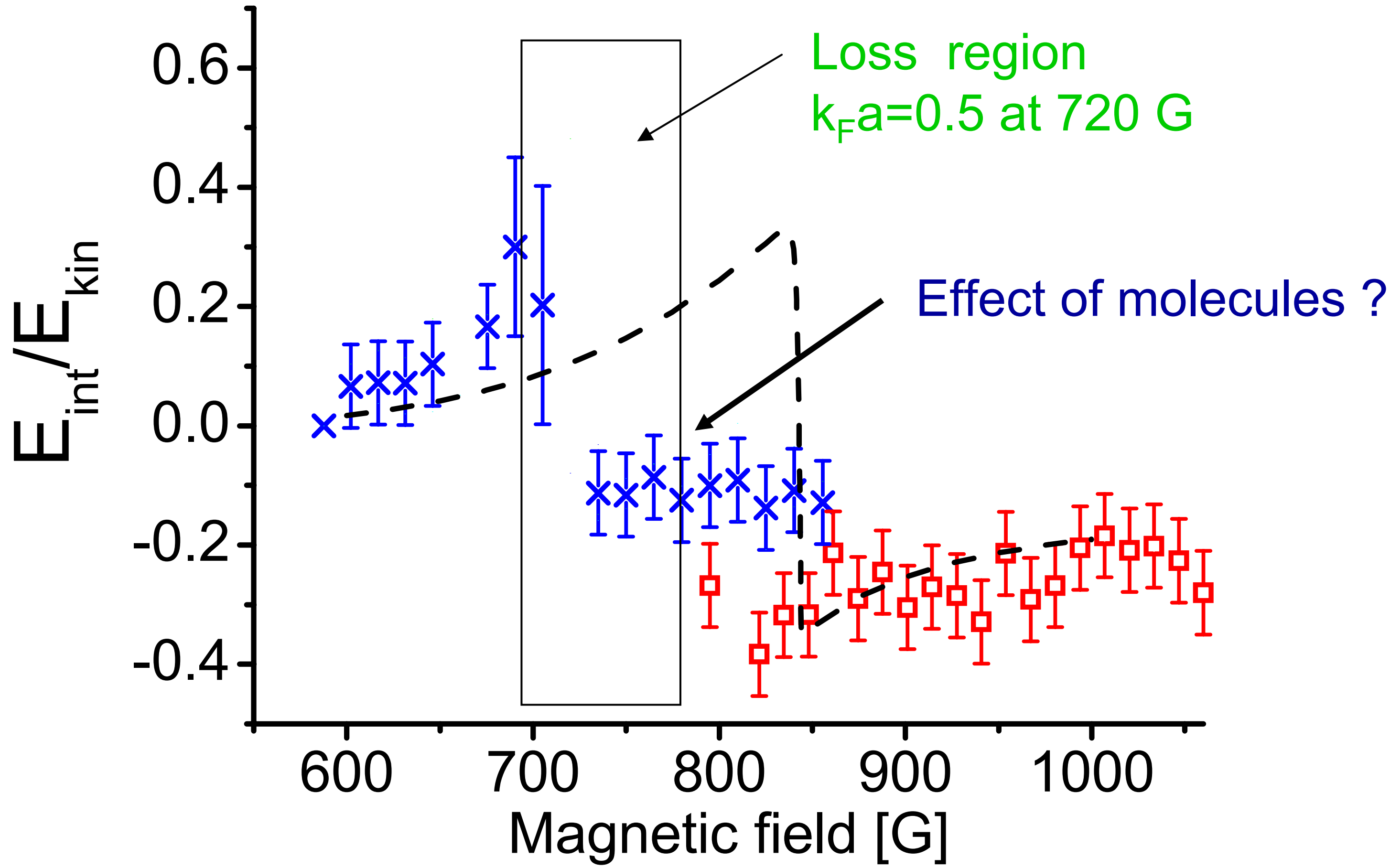


T_F = 2.35 μK
T/T_F = 0.22
N_{total} = 1 10^5

$E_{interaction}$ = -0.35 E_{kin}
k_F |a| > 1
na^3 > 1
Bourdel et al., PRL 2003

Two YAG beams
with 2.5 W and waist of 38 μm

Interaction energy vs magnetic field: surprises



Resonance found at 810(20) Gauss in good agreement with theory

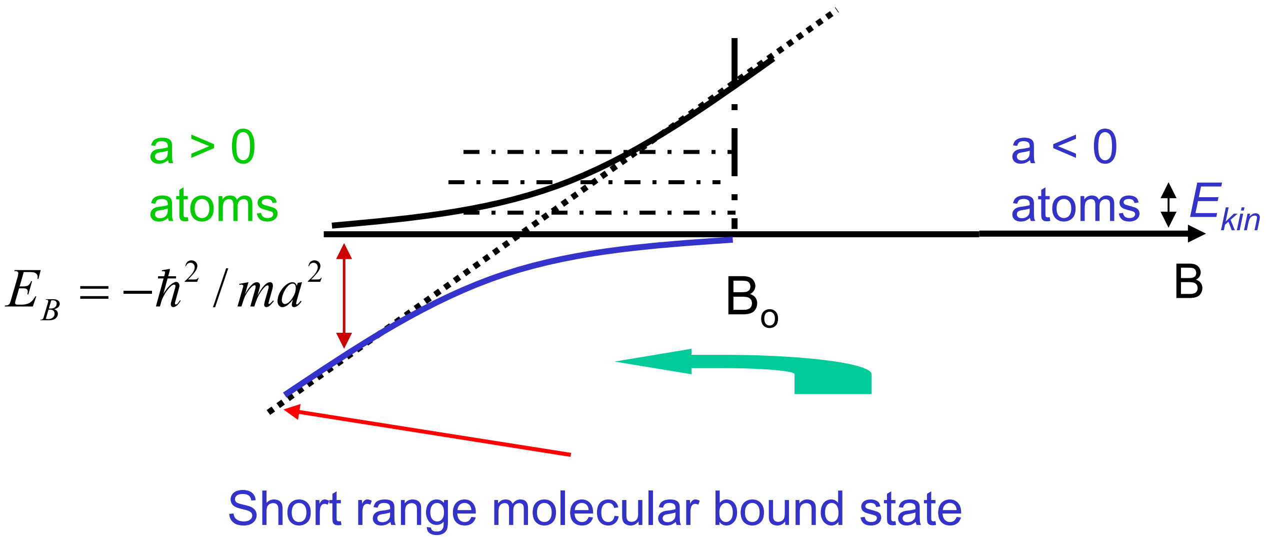
Interaction energy is negative on resonance, as predicted by Heiselberg

Change of sign of E_{int} is shifted from resonance

Strongly interacting Fermi gas: $k_F |a| > 1$

Molecule formation(1): time dependent process

Proposed for bosons in 2000-2001:
Timmermans et al.,Verhaar et al., Julienne, Burnett et al.



When crossing the resonance from right to left, it is energetically favorable to form weakly bound molecules with binding energy E_B which remain in the dipole trap

If slow enough, adiabatic and reversible process: entropy is conserved

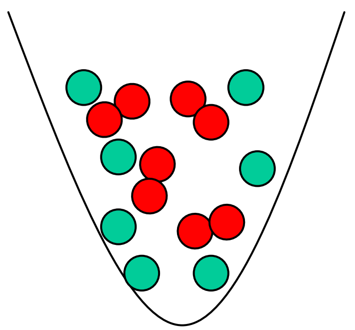
Other method: evaporate fully on the side where a is positive

Molecules formation (2)

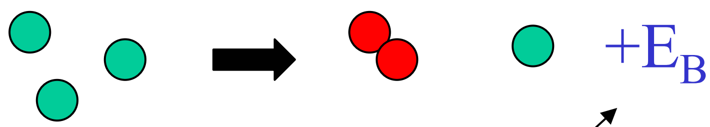
- Three-body recombination [D. Petrov, PRA **67**, 010703 (2003)]
  - Molecules form efficiently in highest weakly bound state

$$\varphi(r) = (r\sqrt{2\pi a})^{-1} \exp(-r/a)$$

Molecules can be trapped!



Binding energy released

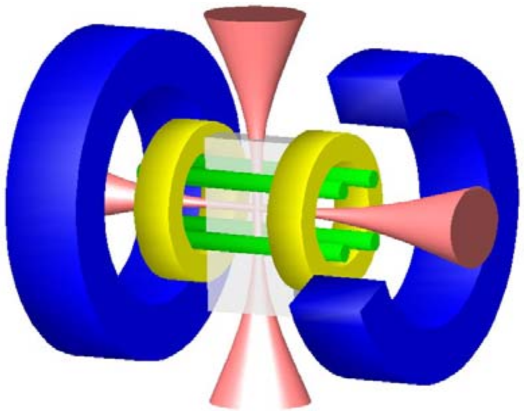


$$E_B = \frac{\hbar^2}{ma^2}$$

$E_B < E_{trap}$ ⟹ Particles stay in trap with heating

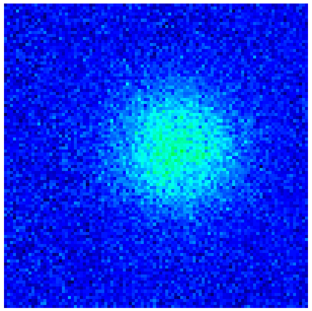
$E_B > E_{trap}$ ⟹ Trap loss

Experimental method for BEC of Li_2 dimers

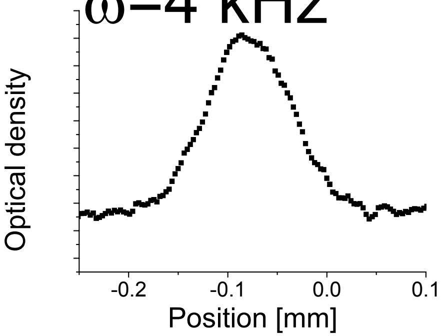


- Sympathetic cooling of 6Li by 7Li
  In magnetic trap until no 7Li left: 10 μK
- Transfer into the optical trap
- Transfer from 3/2, 3/2 to ½, ½ by RF adiabatic passage
- Increase the magnetic field to 1060 Gauss (a<0)
- Prepare 50% mixture: |1/2,1/2>, |1/2,-1/2>, by Zeeman Transfer
- Evaporation of fermions by lowering the trap intensity (factor 10)
- Slow crossing of the Feshbach resonance towards a= +170 nm in 200 ms. Atoms progressively disappear.
- Further evaporation : pure BEC
- Detection

Fermion evaporation



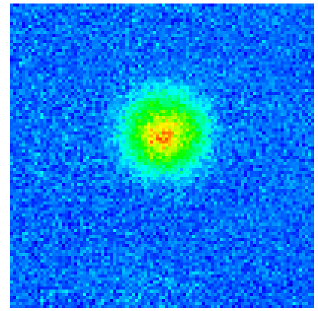
TOF=0.35ms
N=10^5
ω=4 kHz



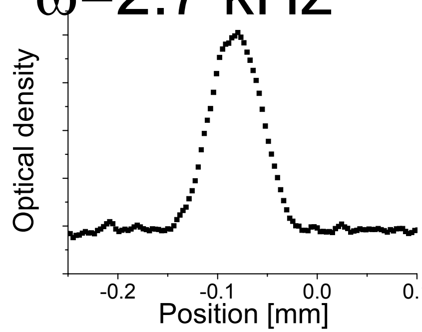
T=10.5 μK

T_F =12 μK

T/T_F =0.87



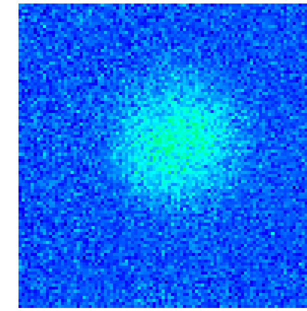
TOF=0.35 ms
N=7.10^4
ω=2.7 kHz



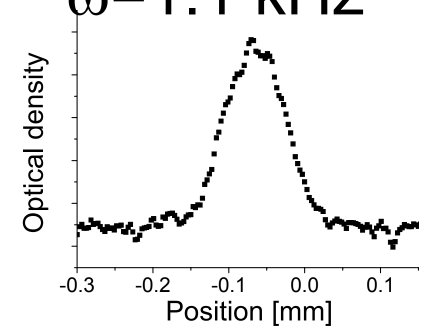
T=3.1 μK

T_F =5.7 μK

T/T_F =0.54



TOF=1 ms
N=5.10^4
ω=1.1 kHz



T < 0.5μK

T_F =2.5 μK

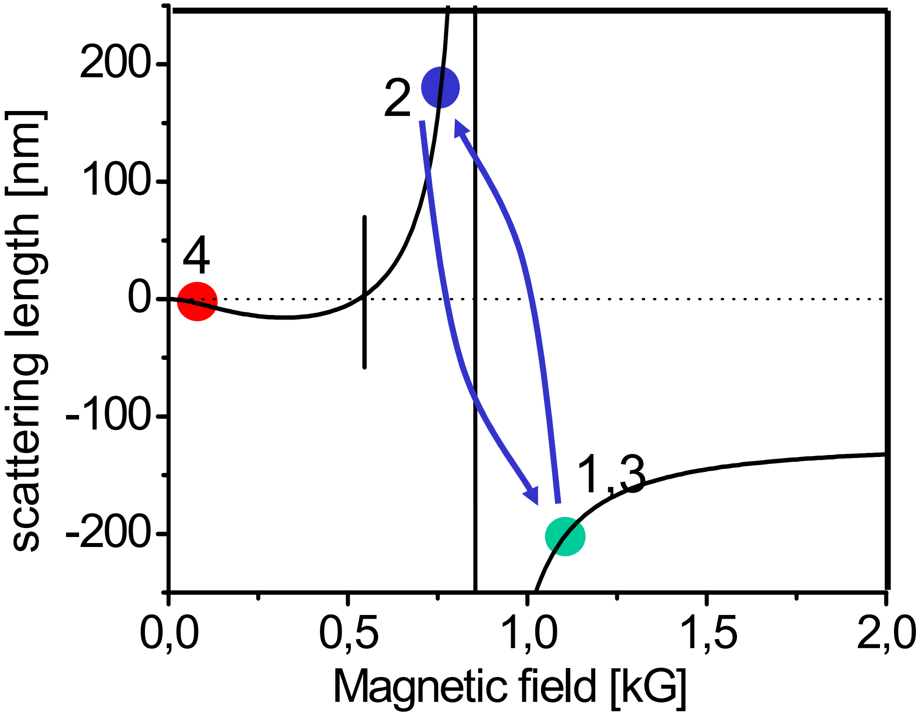
T/T_F < 0.2

How to detect molecules ?

For the probe laser to be on resonance, the magnetic field needs to be turned off. Dimers follow the B field sweep and are not detected.

Double ramp method :

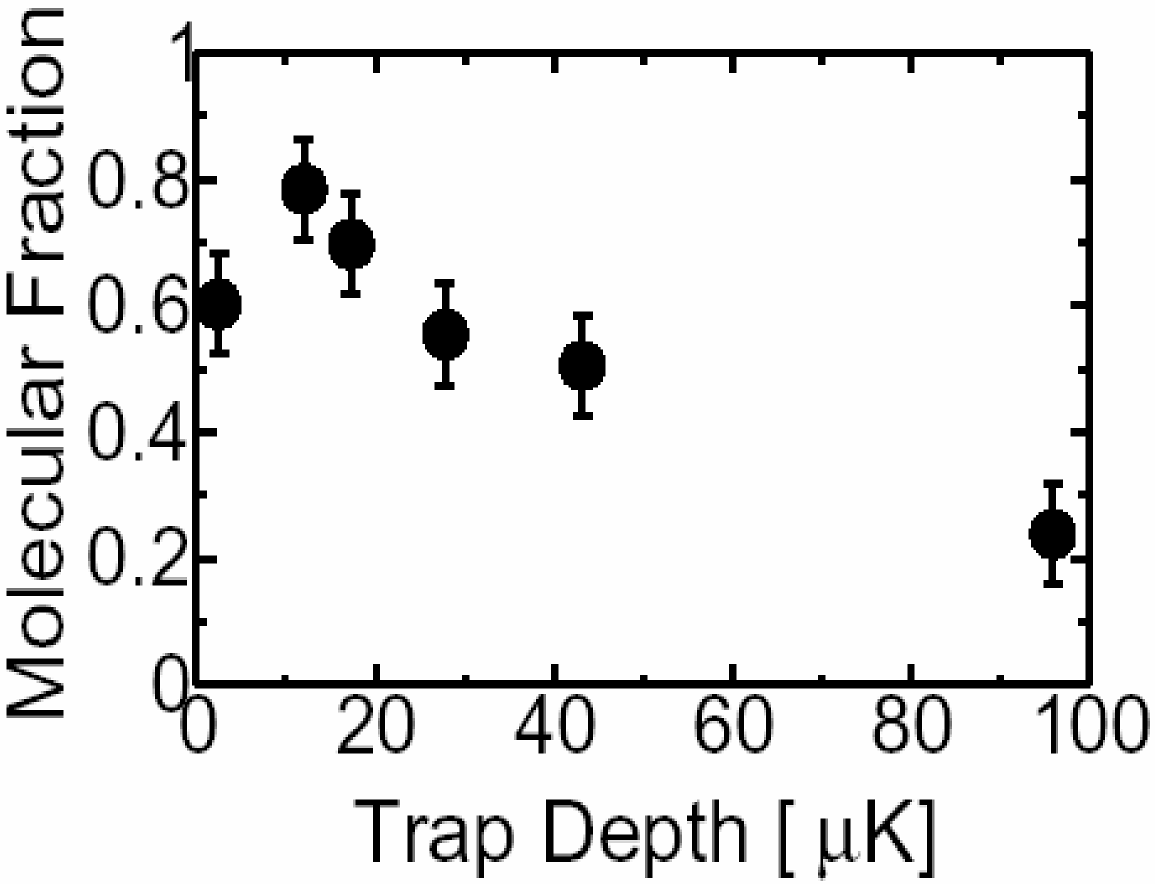
$$2N_{mol} = N_3 - N_2$$



Importance of the ramp speed

Adiabaticity: $\frac{1}{E_B}\frac{dE_B}{dt} << \frac{E_B}{\hbar}$

Efficiency of molecule formation influence of trap depth



Most efficient when:
T/T_F is small and
T/E_B is small.
The colder the better !

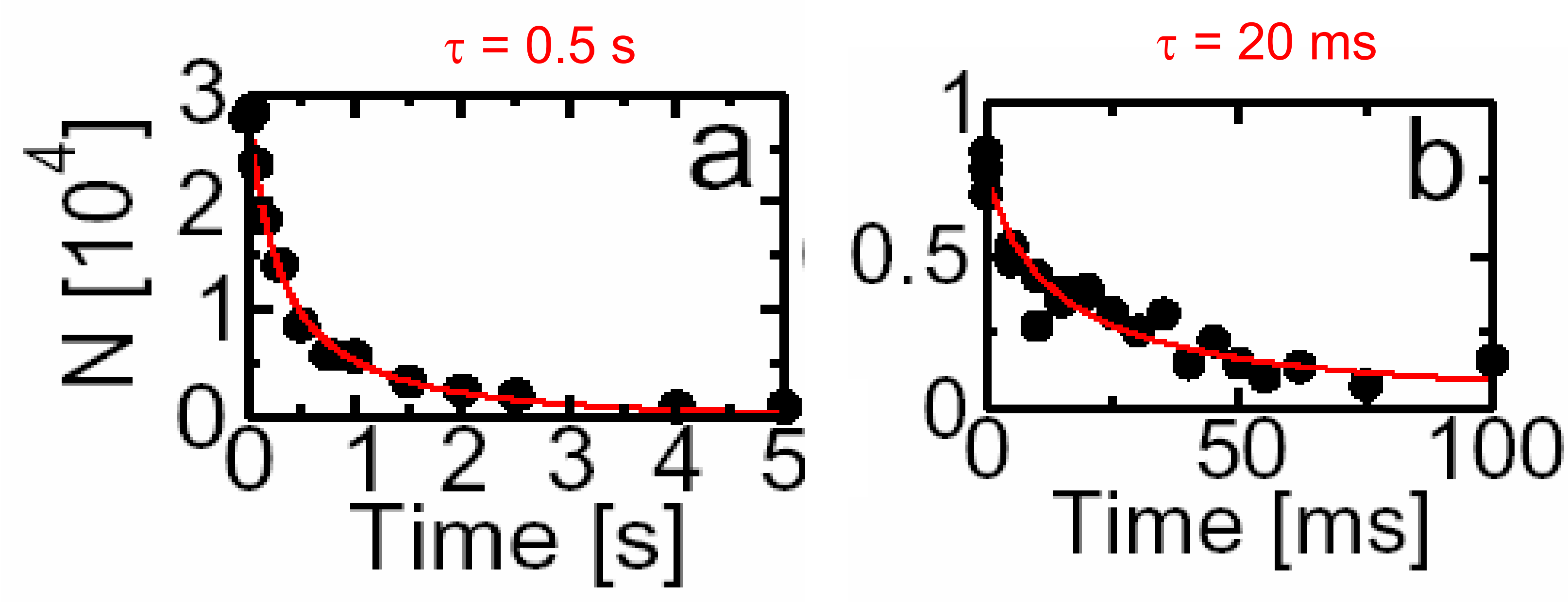
At B= 689 G
a = 78 nm
E_B= 12 μK

T_F= 5 μK
T= 6.7 μK
n_{0m}~4 10^{13} molec/cm^3

At peak : 3 10^4 cold bosonic molecules
Critical temperature for molecules:T_C= 3.5 μK
Factor 2 to gain for BEC of molecules

Cubizolles et al., PRL, 91, 2003

A good surprise:dimers of fermions live very long
Strong dependence upon *a*



a = 78 nm a = 35 nm

Two-body Loss Rate: $\beta \sim 2.4\ 10^{-13}\ cm^3/s$

The larger is a, the longer the lifetime

Role of Fermi statistics

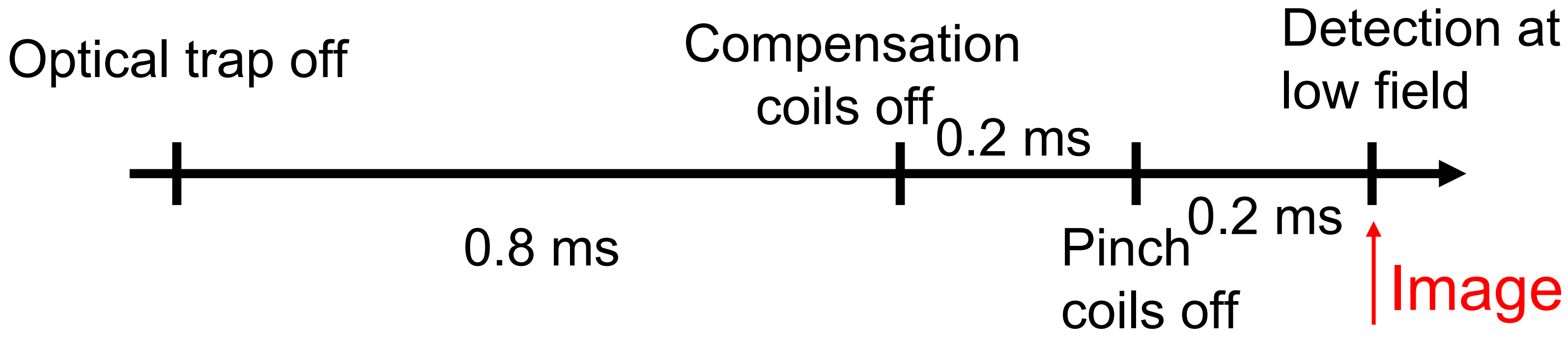
G~ $1/a^s$ with s = 2.55 for dimer-dimer collisions

3.33 for dimer-atom coll.

(D. Petrov, C.S., G. Shlyapnikov)

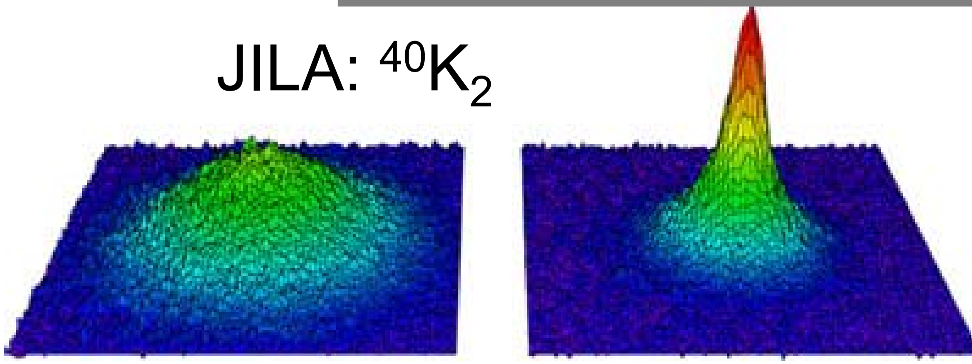
velocity distribution of molecules

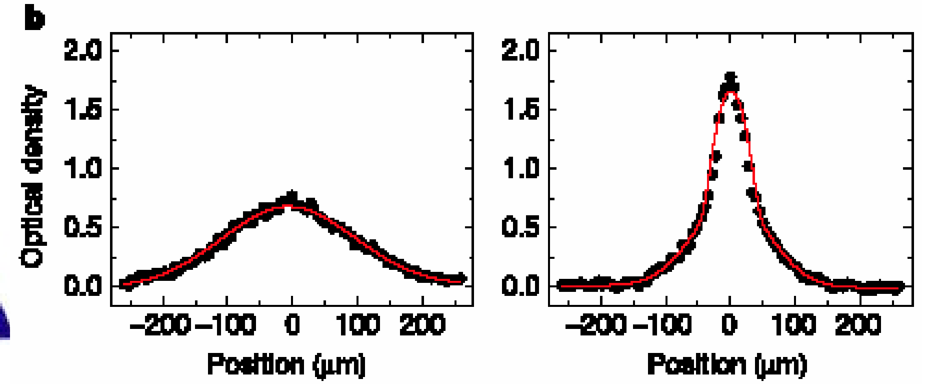
- Low binding energy: possibility to break the molecules with a fast magnetic field sweep
- If molecule is broken: some extra energy is released
- High field imaging of molecules and atoms (Innsbruck)
- RF dissociation of molecules during TOF (JILA)
- Time of flight of molecules (MIT,ENS)
- Switch off trap and keep B field: molecules expand. Then increase B to break molecules at the last moment. Finally switch to B=0 fast (20 μs)



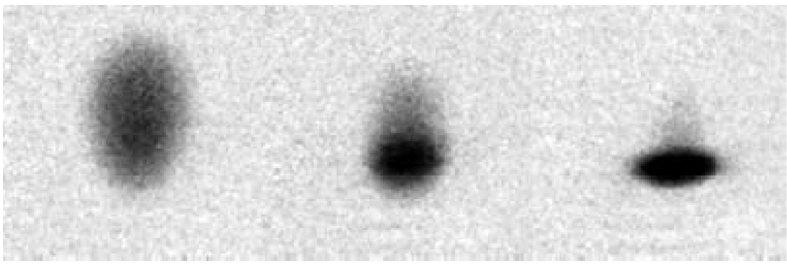
Condensates of molecules

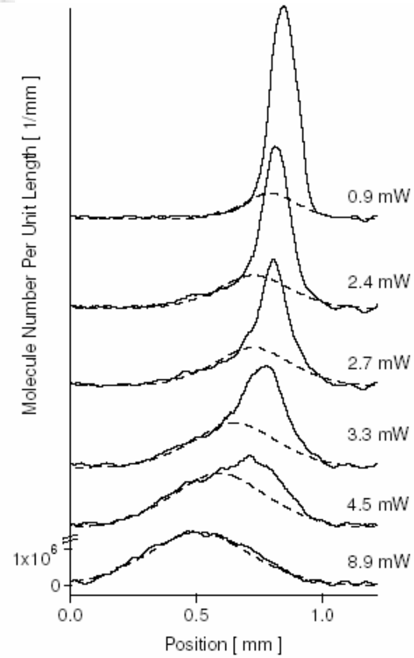
JILA: $^{40}K_2$





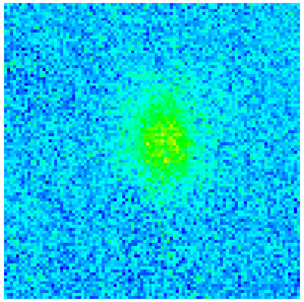
$^6Li_2$:Innsbruck,
MIT

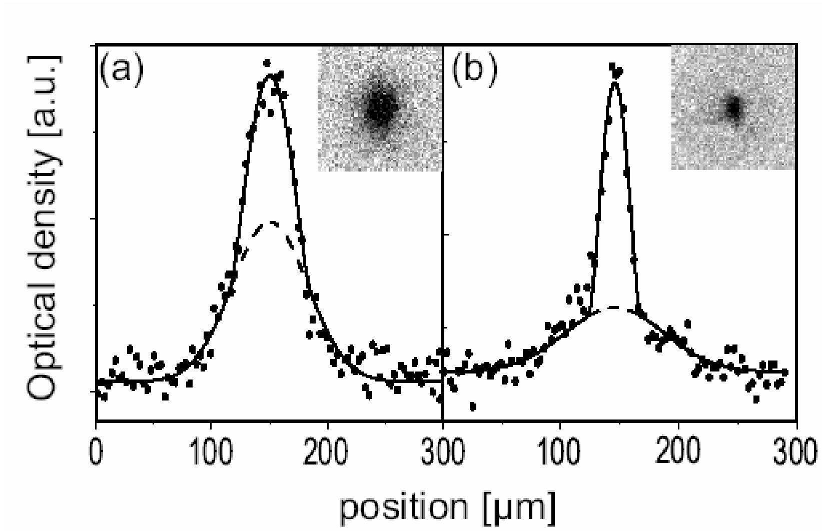




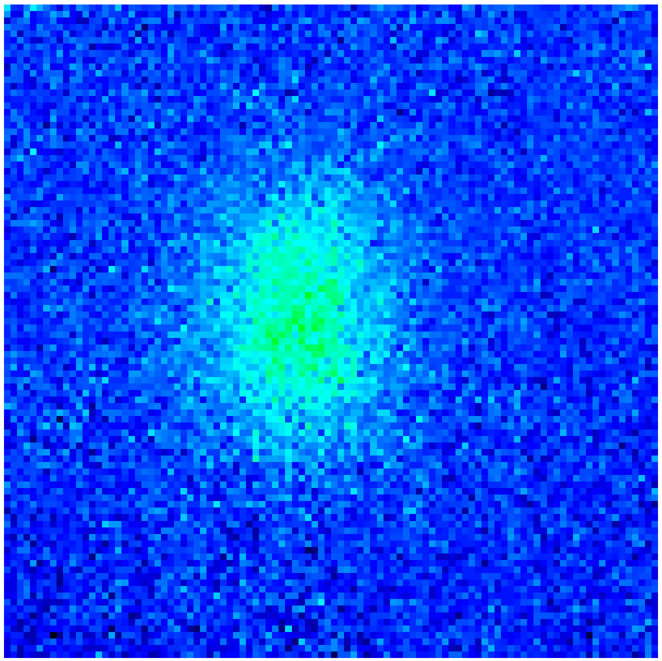
MIT

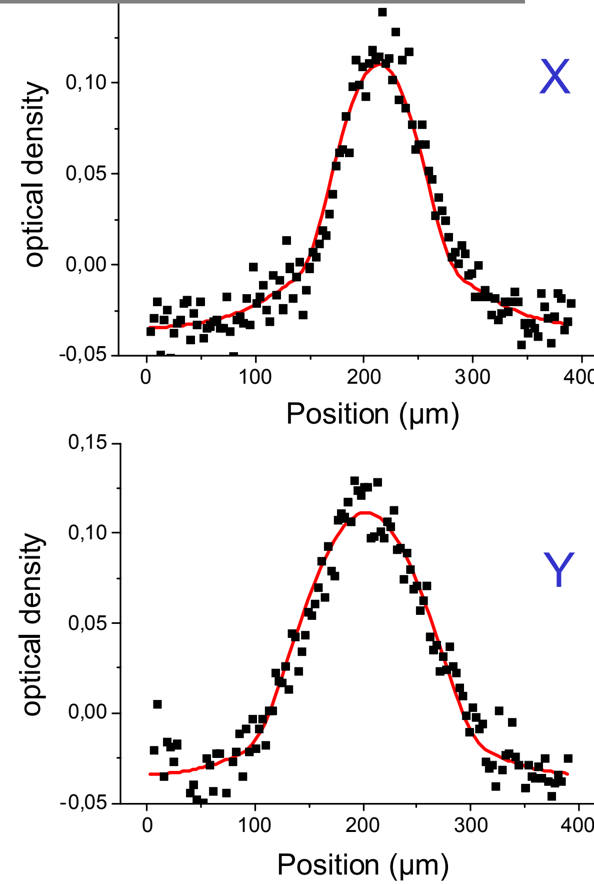
ENS





Bose-Einstein condensation of $^6Li_2$ molecules





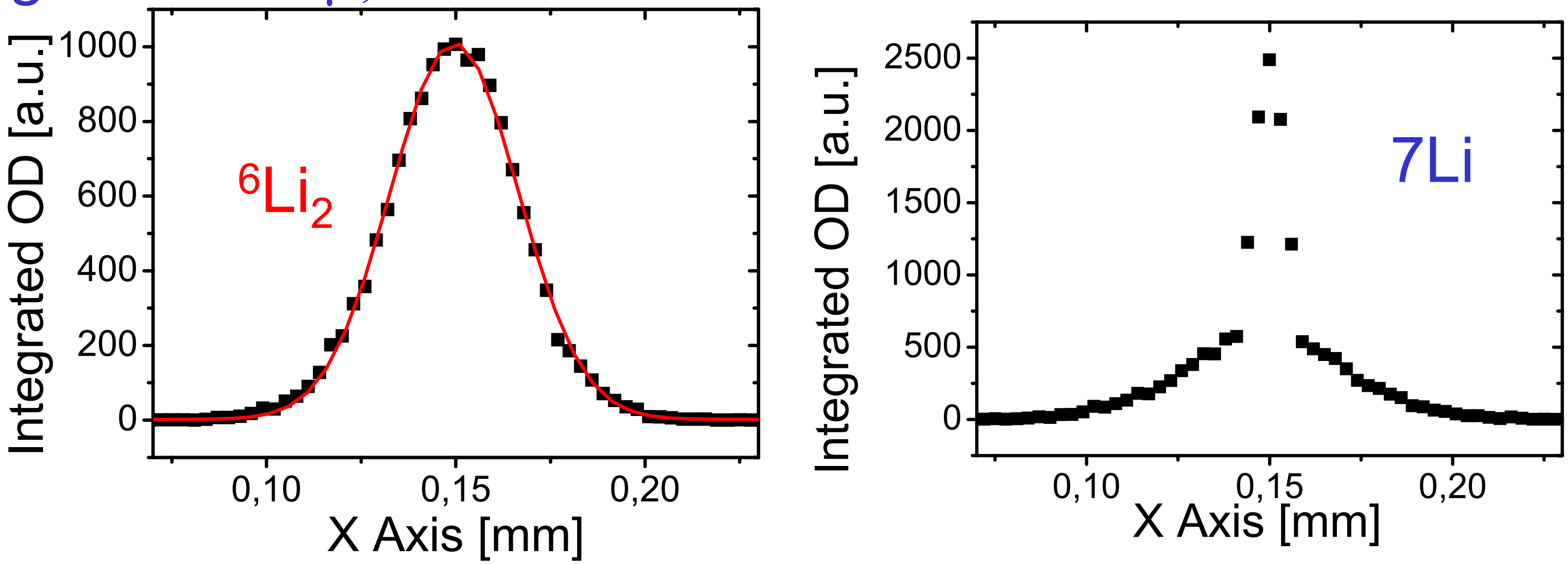
$$
\begin{cases}
N = 7.3 \times 10^4 \\
\omega_x = 2\pi \times 1.4 \text{ kHz} \\
\omega_y = 2\pi \times 3.5 \text{ kHz} \\
\omega_z = 2\pi \times 3.8 \text{ kHz} \\
\text{condensed fraction : } 33\%
\end{cases}
$$

Thermal pedestal is visible

Tc ~ 1.7 μK for 1.5 10^4 mol.

Release energy fits

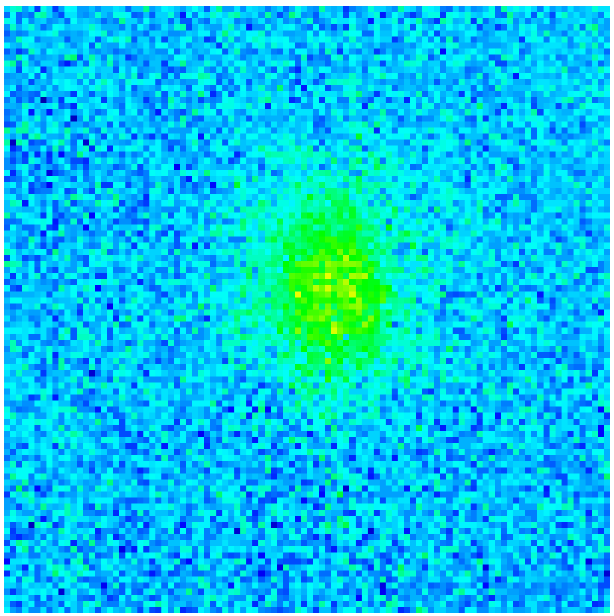
- Model assumption: mean field of the BEC creates an additional potential for the thermal cloud
- Bose distribution of thermal cloud in a new potential is calculated
- Experimental release energy and atom number give T and μ, hence condensed fraction



- T = 1.1 μK = 0.8 Tc

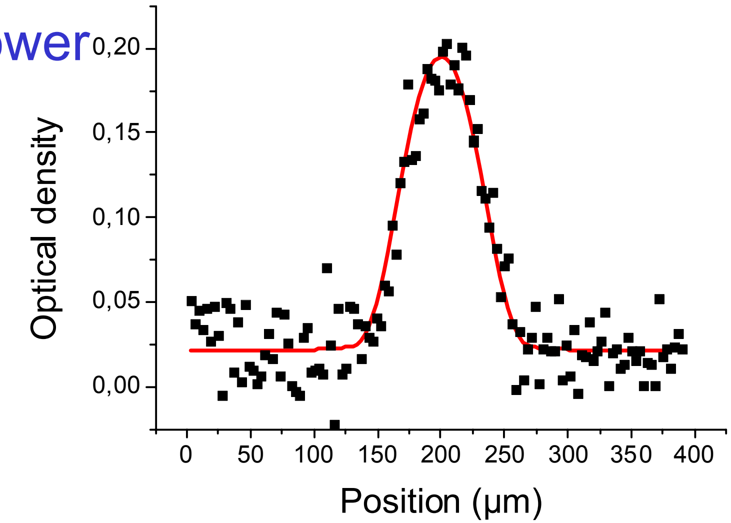
Pure molecular BEC: measurement of a_m

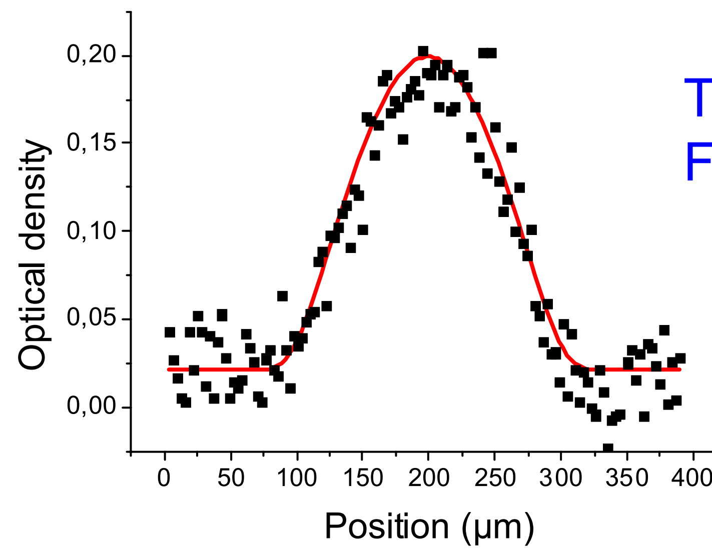
Recompress horizontal beam to full power
Nearly pure condensate
No detectable thermal fraction



$$T \le 0.9\,\mu K = T_c^0 / 3$$

$$\begin{cases} N = 3.9 \times 10^4 \\ \omega_x = 2\pi \times 490 \text{ Hz} \\ \omega_y = \omega_z = 2\pi \times 5 \text{ kHz} \end{cases}$$





Thomas Fermi fit

From expansion

At 770 G $a_{mm} = 170^{+100}_{-60}\ nm$

Strongly interacting condensate

Pure condensate parameters for 770 G, a_{mm}=+170 nm

Theory: a_m=0.6a= 0.6 306= 183 nm D. Petrov, G. Shlyap.,C.S.

2 10^4 molecules in a trap with

Peak density 6 10^{13} mol/cm^3 for ω_{bar}= 2.2 kHz

$n_m a_{mm}{}^3$= 0.3

μ/k_B= 0.8 μK= Tc/3

Shift of Tc by interactions should be easy to study !

Condensate lifetime:

0.3 second at 715 G, a_m = 66 nm

3 seconds at 770 G, a_m = 170 nm

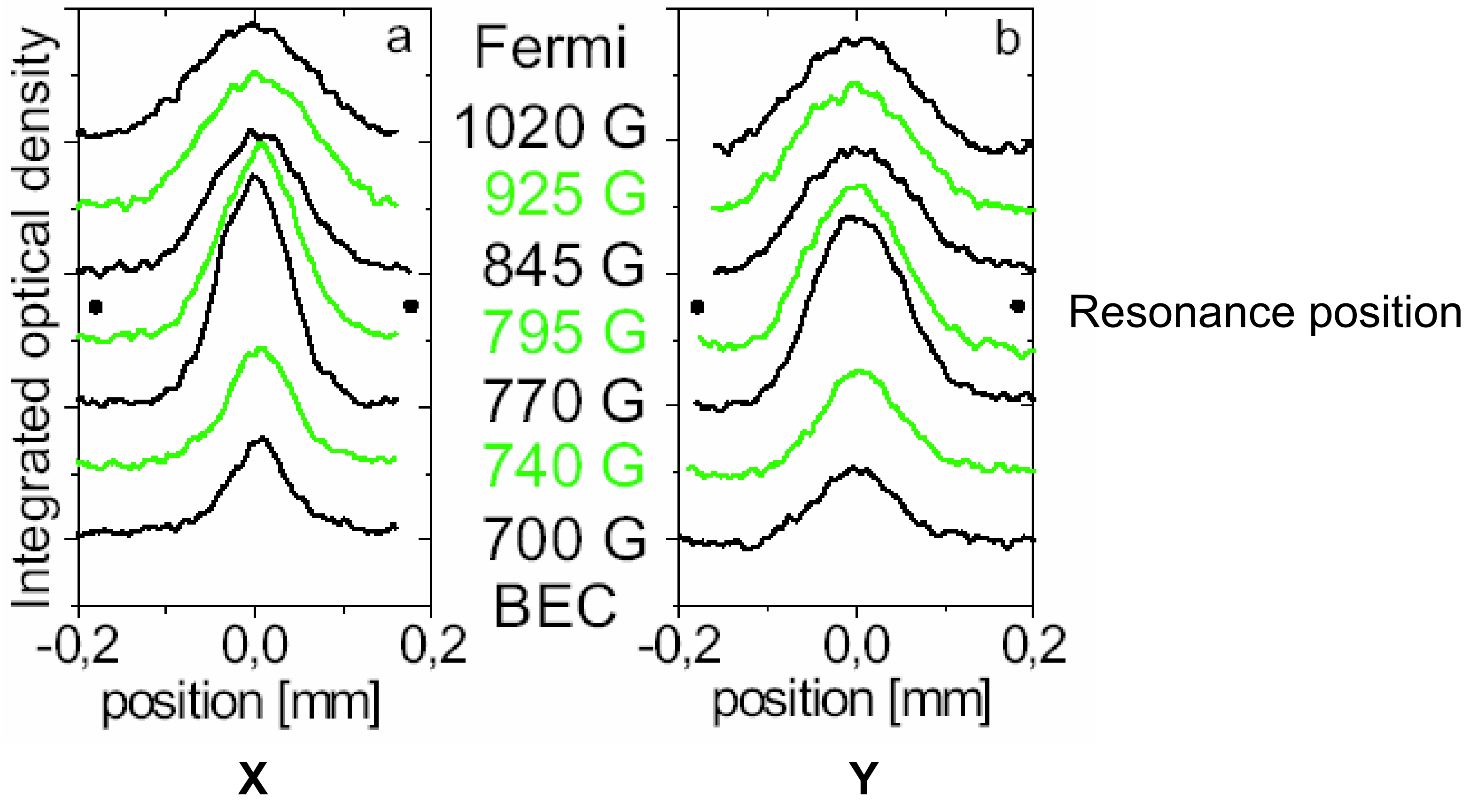
30 seconds at 1060 G, a = - 167 nm

Rate constant: $G \sim a^{-1.9\pm0.8}$ Theory $G \sim a^{-2.55}$

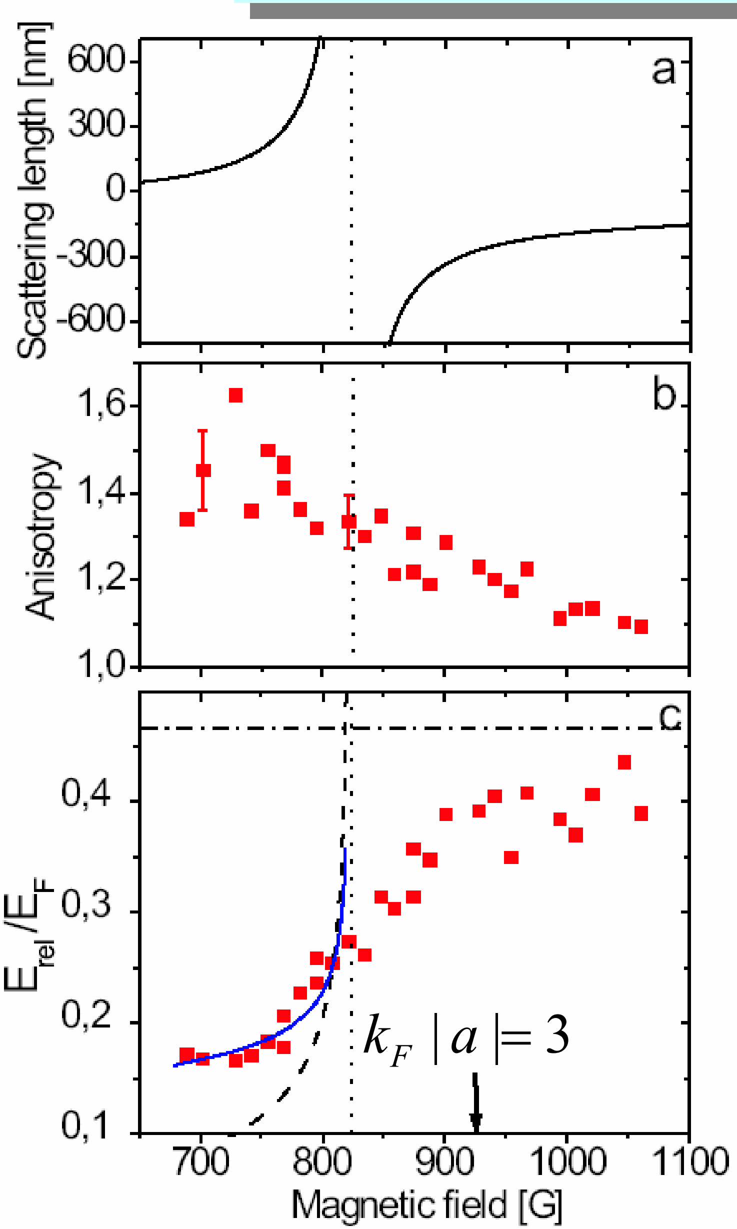
An ideal playground for studying beyond mean field effects

Study of the BEC – BCS crossover region

Prepare pure condensate: 4 10^4 molecules
Change magnetic field
Take 1.4 ms TOF image



Study of the crossover BEC -BCS



Anisotropy persists on a<0 side

Composite Fermi-Bose system near resonance.

At 820 Gauss,

$$\beta = E_{\text{int}} / E_{kin} = -0.55(10)$$

Mean field model with finite T

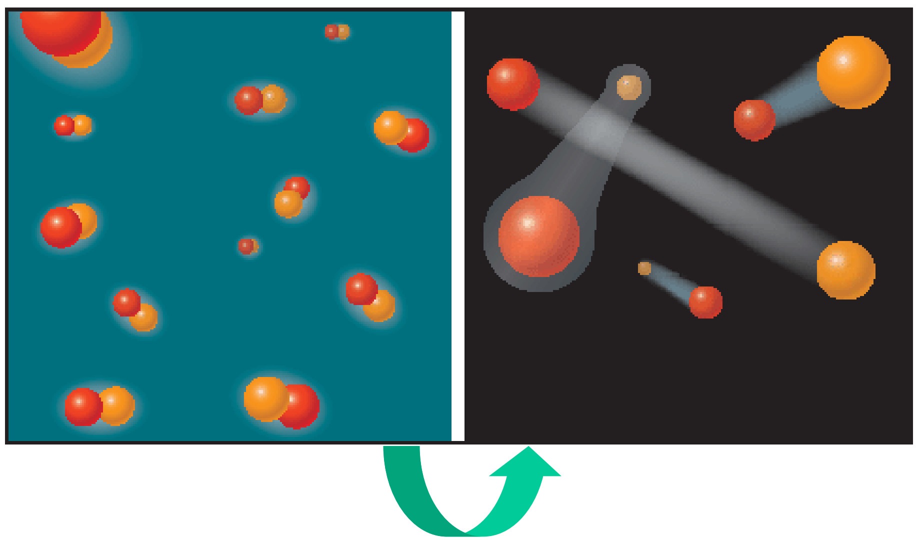
$$For\ B = 720\,G, \quad N_0 / N = 0.70$$

$$and \quad T = T_c^0 / 2 = 1.2 \mu K$$

Fermi superfluid

Remains to be seen !
Produce BEC of molecules with $T/T_{BEC} << 1$
Cross the Feshbach resonance isentropically towards $a < 0$, currently T/T_F <0.1.

$a > 0$



$a < 0$

According to L. Carr, G. Shlyapnikov and Y. Castin, cond-mat/0308306 this produces a deeply degenerate Fermi gas with $T=0.01\ T_F$ or lower !
Thus $T < T_{BCS}$ for $(k_F a)_{final} \sim 0.5$
Unambiguous detection of superfluid required !!

Perspectives

- Strongly interacting Fermions

BEC of molecules in the large a limit: non ideal effects
Analyze crossover Condensate of molecules/ superfluid Fermi gas
(Nozières, Randeria , Ohashi, Griffin)

- Search for clear signature of fermionic superfluidity

Theory of Fermi gas expansion

- Mott transition for fermions in an optical lattice (Hoffstetter et al.)

Simulate various many- body hamiltonians in periodic structures
Strongly correlated fermions domain is very vast !

- Bosons/fermions mixtures
  - Collapse of Fermi gas observed in Firenze
  - Pairing mecanism mediated by bosons
  - Improve on T/T_F
  - Better thermometry for $T/T_F \ll 1$